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Life Cycle Assessment in the Marine Renewable Energy Sector

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Abstract

Reliable figures for the life cycle impacts of power generation are needed to inform developments of the energy system and enable market trading of environmental credits. Marine energy is likely to form a significant part of the future energy mix in the UK and the Pelamis wave energy converter is emerging as one of the most promising devices in this sector. This study examines the environmental impacts of the Pelamis. By comparison with the results of an earlier carbon and energy audit for the same device, the implications of practitioner decisions on LCA results are investigated, specifically with regards to the allocation method for dealing with materials recycling.

Keywords: Life cycle assessment, wave energy, recycling methods, renewable energy, carbon emissions

Introduction

The drive to reduce Greenhouse Gas (GHG) emissions has led to the development of new technologies to harness renewable energy. In the UK marine energy has the potential to supply around 20% of electricity demand, so significant developments are occurring in the marine renewables sector (Callaghan and Boud, 2006). However, while marine energy sources are themselves ‘carbon-free’, there are wider environmental impacts associated with the process of converting this energy into electrical power. In order to make informed decisions for future developments of the energy system, and to confidently evaluate environmental impacts for market trading, it is important to develop a detailed understanding of the life cycle impacts that arise indirectly due to the manufacture, operation and decommissioning of generators and network infrastructure.

Unlike conventional power generation and wind power there is little consensus on the general design of wave and tidal energy converters. New technologies are constantly emerging and few full Life Cycle Assessments (LCAs) have been carried out to date. Some high-level analyses, however, have been published, assessing the embodied carbon and energy of the material content of marine devices (Banerjee *et al.*, 2006; Woollcombe-Adams *et al.*, 2009). This paper details a full LCA of the Pelamis, one of the most promising devices in this sector (Figure 1). The analysis follows the framework described in the ISO 14040 series of standards, which allows a number of practitioner assumptions (ISO, 2006).

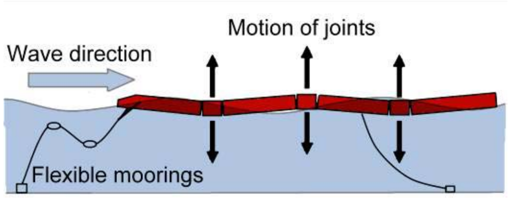
Figure 1: The Pelamis (PWP, 2011)

The results are compared to an earlier carbon and energy audit of the same device to examine how variations in assumptions and methodology, specifically that of recycling allocation, affect LCA results (Parker *et al.*, 2007). The findings will be used to better inform comparisons of the environmental impacts of different marine energy technologies.

Developed by Pelamis Wave Power Ltd, the P1 version of the Pelamis wave energy converter was successfully installed at the world's first commercial wave farm at Aguaçadoura, Portugal, in 2008. The experience has been fed into the second-generation P2 device currently on test at the European Marine Energy Centre. Several commercial projects for the P2 are under development, and lease agreements have been agreed for two Scottish farms comprising around 70 devices (PWP, 2011).

The Pelamis is a semi-submerged snake-like offshore wave energy converter. The P1 version is 120 m long, 3.5 m in diameter and rated at 750 kW. It has four cylindrical sections linked by three Power Conversion Modules (PCMs) at the hinged joints. The moorings allow the Pelamis to face into the oncoming waves and the joints flex vertically and horizontally as the wave front passes (Figure 2). This motion is resisted by hydraulic rams that pump high-pressure oil into hydraulic motors, in turn driving generators. The resistance of the rams can be tuned to maximise power capture in small sea states while protecting the device from potentially damaging storm waves.

Figure 2: Side view of Pelamis (Parker *et al.*, 2007)

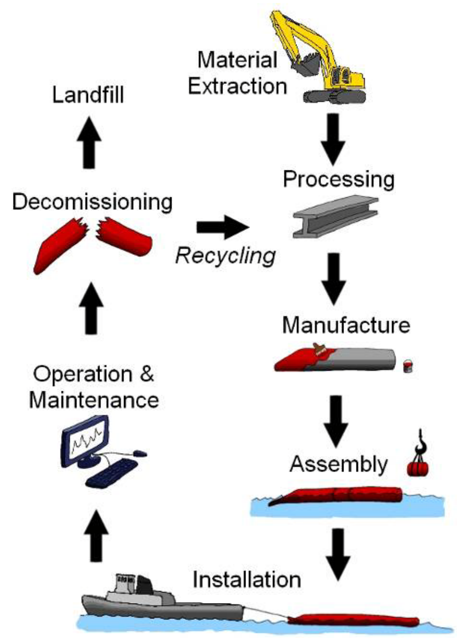


Goal and Scope

In 2007 an in-depth life cycle carbon and energy audit of the Pelamis P1 device was published by Parker *et al*. (2007). It found that the energy and carbon intensities of the generated energy were 293 kJ/kWh and 23 gCO_2/kWh generated. This paper expands the analysis to a full life cycle inventory and impact assessment. The results of the two studies are compared to investigate the effect of practitioner assumptions, and the comprehensive results also highlight the components, materials or life cycle stages with the largest environmental impacts.

The system boundary of the current study encompasses the entire life cycle from "cradle-to-grave" (Figure 3). Physically this includes the device, its moorings and sub-sea connecting cable, but excludes all downstream electrical components. The functional unit is one kilowatt-hour of output power (1 kWh), with a calculation reference flow of 1 Pelamis device.

Figure 3: Pelamis Life Cycle



To facilitate comparison with the analysis carried out by Parker *et al*. (2007), the fundamental assumptions and base data have been retained. In line with this it is estimated that the power output of a single device installed at a typical site off the coast of Scotland will average 2.97 GWh/year over the 20-year design life. The successful installation at Aquaçadoura found that the Pelamis performed as expected, so this assumption is still considered valid (PWP, 2011). The study assumes that all major components and sub-components are manufactured in the UK and subject to UK energy statistics and transport distances. The typical wave farm is within 200 miles of a commercial port.

The study was carried out with SimaPro (version 7.2 PhD). Life cycle inventory data was mostly sourced from the Ecoinvent database, which is recognised as one of the most comprehensive sources of such data in Europe (Ecoinvent, 2010). Data not available within Ecoinvent was sourced from alternative datasets or literature. The EDIP 2003 impact assessment method was applied, as it includes a broad range of impact categories and was developed for use with Ecoinvent data, minimising inaccuracies caused by mismatches.

Life Cycle Inventory Analysis (LCI)

The quantities of raw materials, processing and manufacturing methods, and transportation were based on figures derived from the manufacturer's own records (Parker *et al.*, 2007).

The main structure of the Pelamis is formed from cylindrical steel tube sections with sand used as ballast. The mooring and cabling system includes several plastic components. Electrical equipment, housed in the nose tube, collects and transforms the power to high voltage for export to shore. The hydraulic power-take-off, generators and control equipment are located in the PCMs.

A mass-based analysis was carried out for the structure, hydraulic system and mooring components (Table 1). Such data was not available for the pre-fabricated components, such as fixings and electrical items, and sourcing detailed LCI data for these is time-consuming, so cut-off criteria were defined to exclude inputs without a significant environmental impact (ISO, 2006). These criteria were applied to a preliminary cost-based analysis of carbon emissions and energy consumption, finding that the transformer, main generators and switchboard should be included in the study. Other pre-fabricated components were excluded as they contributed less than 1% to the total impacts.

Table 1: Material quantities in the Pelamis P1

Stock Material	**Mass (kg)**
Steel	561954
Sand	475722
Stainless Steel	550
Nylon 6	416
Polyurethane	343
Glass Reinforced Plastic (GRP)	90
PVC Pipe	55

The next life cycle stage involves the transportation of components from the manufacturing plant to the dockyard for final assembly. A range of sea vessels are then used for installation of the moorings and power cabling, sea trials, tow to site and latching to the moorings. Annual maintenance operations also involve the use of sea vessels. Data for this stage was based on manufacturer estimates, as a complete picture of real operation and regular maintenance has not been registered to date. These estimates are understood to be conservative, with the key aim of confirming and ensuring survivability. The device itself has very few operational requirements, as remote monitoring and control is entirely computer-based, onshore, so no allowance has been made for the small environmental impacts of this. Ecoinvent includes mass-distance data for freight transport. Other processes and sea vessel operations were approximated from fuel consumption data.

It is expected that decommissioning will involve sea vessel operations associated with the recovery of all hardware. The waste will be split into two streams, with the majority of metals being recycled (90%), and the remainder of the waste going to landfill. UK-specific LCI data for landfill is not readily available so average European data was selected from the European Life Cycle Database (v2.0). Where this was not available the emissions were approximated using Ecoinvent data for Switzerland.

Recycling of waste materials has a significant effect on the environmental impact of a device, as the use of recycled materials avoids the greater impact of primary material production. This results in an environmental credit. Marine energy converters may be responsible for both the consumption and creation of recycled materials, so it is not immediately clear where this environmental credit should be applied. Currently there is no consensus on the most appropriate methodology for allocating the benefits of recycling, as it can be applied to the product that *uses* the recycled material, the product that *produces* the recyclable scrap, or *both* products (Jones, 2009).

The recycled content approach is one of the most commonly applied allocation methods, as it is used in the assessment of cradle-to-gate impacts of materials for LCI datasets. All credit is allocated to the product that uses the recycled material, as recycling is of no benefit without the resulting material being consumed. However, recycled materials could not exist without a primary product to generate them, and therefore it could be argued that the recycling credit should be allocated to the product that is recycled. This can be calculated using closed loop substitution, the method recommended by the International Iron and Steel Institute (IISI, 2002). This was the method applied by Parker *et al.* (2007).

The 50:50 method is a compromise that recognises that both the upstream and downstream products are necessary for recycling, and assumes that half of the benefit goes to each product (Jones, 2009). The 50% figure is fairly arbitrary and open to discussion, but it does ensure that the results of different studies can be combined without double-counting. This is the only method that achieves the goal of promoting sustainable design that minimises primary material use and maximises recyclability of materials at the end-of-life.

In order to examine the effects of applying these different methods, the results are presented for all three: The Recycled Content (RC) method, the substitution method (Sub) and the 50:50 method (50:50).

Table 2: Results of life cycle impact assessment

Impact potential	**Total**			**Impact potential**	**Total**		
	RC	**Sub**	**50:50**		**RC**	**Sub**	**50:50**
Global warming (gCO_2e/kWh)	30	24	27	Hazardous waste (mg/kWh)	2.3	1.4	1.8
Acidification ($x10^{-3}$ m^2/kWh)	2.9	2.6	2.7	Slags/ashes (mg/kWh)	3.7	3.7	3.7
Ozone depletion (µgCFC-11e/kWh)	2.3	2.2	2.3	Human toxicity			
Ozone formation				*Air (m^3/kWh)*	640	480	560
Vegetation (m^2.ppm.h/kWh)	0.42	0.38	0.40	*Water (m^3/kWh)*	1.6	0.63	1.1
Human ($x10^{-5}$ pers.ppm.h/kWh)	2.8	2.6	2.7	*Soil ($x10^{-3}$ m^3/kWh)*	5.5	4.6	5.0
Eutrophication				Ecotoxicity			
Terrestrial ($x10^{-3}$ m^2/kWh)	5.3	5.0	5.2	*Water chronic (m^3/kWh)*	10	9.5	9.9
Aquatic (N) (mgN/kWh)	21	20	20	*Water acute (m^3/kWh)*	1.9	1.7	1.8
Aquatic (P) (mgP/kWh)	9.8	8.2	9.0	*Soil chronic ($x10^{-3}$ m^3/kWh)*	2.9	2.4	2.7
Radioactive waste (µg/kWh)	470	390	430	Bulk waste (g/kWh)	7.9	10	9.0

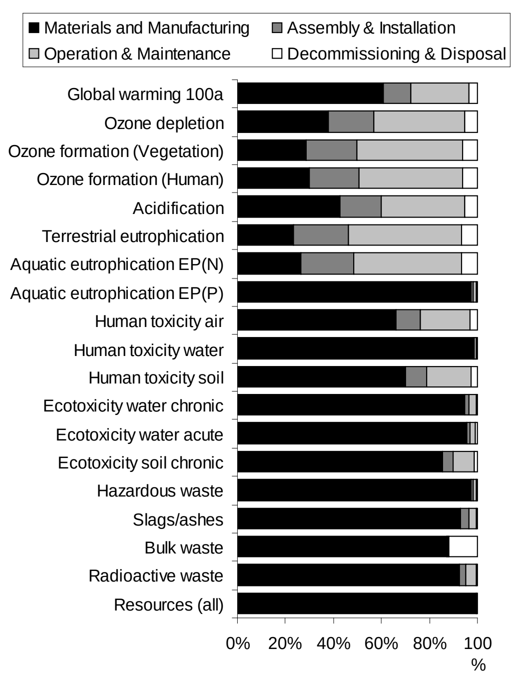
Results

All results are presented in relation to the functional unit of 1 kWh of output power. The life cycle inventory produces data for the energy consumption associated with the device (Table 3), giving an energy intensity of 311-381 kJ/kWh, which corresponds to a payback time of 21-25 months. Over 90% of this embodied energy is associated with the manufacturing stage, mostly due to the steelmaking process.

Table 3: Energy intensity

Life Cycle Stage	Energy Intensity (kJ/kWh)		
	RC	**Sub**	**50:50**
Materials & Manufacture	348	402	375
Assembly & Installation	11	11	11
Operations & Maintenance	19	19	19
Decomg. & Disposal	3	-121	-59
TOTAL	*381*	*311*	*346*

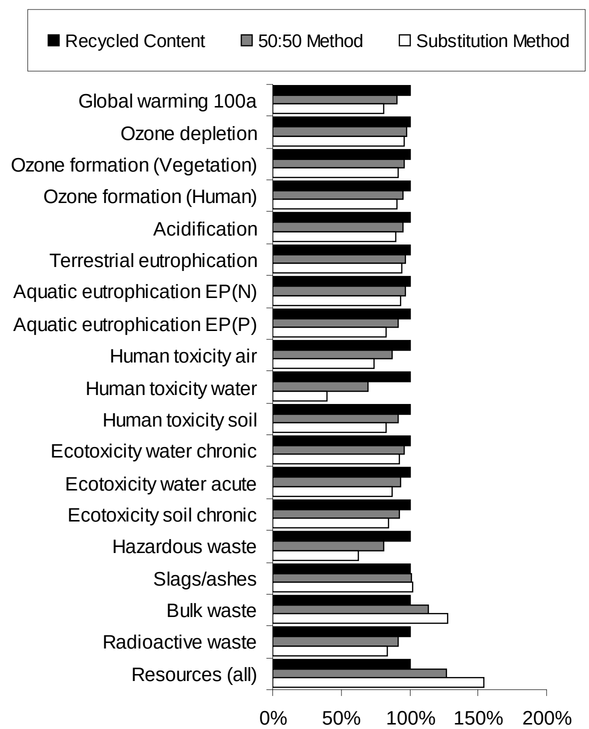
Figure 4: Life cycle stage analysis (RC method)



The full environmental impacts of the Pelamis are summarised in Table 2 on the preceding page. The GWP is of particular interest: 24-30 gCO_2e/kWh. Taking the carbon intensity of the offset grid electricity as the 5-year average of 0.499 $kgCO_2/kWh$, in accordance with Defra/DECC guidelines (Hill, 2009), carbon payback will be achieved in 12-14 months. This will be shorter if the device offsets only marginal carbon intensive generation.

Manufacturing and maintenance shipping operations are significant contributors across all categories (Figure 4). It can be seen in Figure 5 that the substitution method generally gives the most optimistic results, due to the average recycled content of European steel being around 40% (Classen *et al.*, 2009), and the assumed recycling rate for waste being 90%.

Figure 5: Effect of recycling method on results



Effect of Practitioner Assumptions

This study was carried out to a higher level of detail than that published by Parker *et al.* (2007), with a different software tool and different LCI datasets. In particular freight transport and waste treatment were dealt with more comprehensively. However, a comparison of the analysis results shows that it is the recycling method that has the most significant effect. If the recycled content method is applied, the results of the current study are approximately 30% greater than those found by Parker *et al*. However, by applying the same substitution method as that used in the earlier study, the difference is reduced to approximately 5% (Table 4). The inclusion of all greenhouse gases increases the carbon intensity by 3-6%.

Table 4: Comparison of results

Impact	**Current study**	**Parker *et al.***
GWP (g CO_2-e/kWh)	24	-
CO_2 Emissions (g/kWh)	23	23
Embodied Energy (kJ/kWh)	311	293

Conclusions

This paper presents a detailed Life Cycle Assessment of the Pelamis wave energy converter. It expands an earlier carbon and energy audit to a full assessment of environmental impacts. The resulting carbon intensity of 24-30 gCO_2e/kWh generated and energy intensity of 311-381 kJ/kWh generated compares well with the earlier study. It highlights that the choice of recycling method can significantly affect the LCA results so it is important that assumptions about recycling credit are clearly stated for future studies in this sector. As the 50:50 method provides an average of both figures it is considered to be the most appropriate for marine energy converters.

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